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A Proposed Orbiting X-ray Telescope*†


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A Proposed Orbiting X-ray Telescope* †

In the x-ray region the index of refraction of all materials is very slightly smaller than one. It is given by classical electron theory^{(1) (2)} as:

$$(\text{Eq. 1}) \quad n = 1 - \delta = 1 - \frac{N_e e^2 \lambda^2}{2\pi m c^2}$$

N_e = number of electrons per cm^3 whose binding energy is smaller than the energy of the incident x-rays.

e = electron charge [e.s.u.]

λ = wavelength [cm]

c = velocity of light cm sec^{-1}

Since $\delta \ll 1$ this leads to a critical angle of total reflection of

$$\theta = \frac{1}{\sqrt{2\delta}}$$

which is of the order of 1° for x-rays in the 1 \AA region.

(1) M. A. Lorentz, The Theory of Electrons, Leipzig, Teubner 1916.

(2) For a review of the literature see Kirkpatrick and H. H. Pattee, Jr., Handbuch der Physik, Springer 1957, Vol. 30.

* This study was supported by the National Aeronautics and Space Agency, Grant # NSG 578.

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With the possibility to lift instruments above the earth's atmosphere and to observe in wavelength regions so far inaccessible it is of interest to examine the possibility to design a totally reflecting x-ray telescope. The basic design feature of the proposed instrument is the use of one or more concentric slices of paraboloids arranged to have a common focus. (Figure 1) (It has only recently come to my attention that an identical design was proposed earlier by Giacconi and Rossi.⁽³⁾)

The cost of the instrument is obviously determined by the two parameters, ΔL and r_2 which describe the physical dimensions of the mirror ring. One is then left with a choice of two other parameters, the smaller radius R_1 and the mirror material and compromises have to be found concerning these two.

Choice of Material:

Since the critical angle of total reflection is proportional to the electron density and hence roughly proportional to the density of the mirror material, the

(3) R. Giacconi and B. Rossi, Journal of Geophysical Res. 65, 773 (60).

best choice would seem to be to use as dense a material as possible, however, the absorption goes up with the atomic number Z and reduces the reflectivity, especially at longer wavelengths. Also, in high Z materials the inner electrons are too tightly bound to contribute to the total reflection which is due only to electrons whose binding energy is smaller than the energy of the radiation to be reflected. For this reason it is preferable to use medium density low Z materials.

An examination of the elements and of inorganic compounds yields the following as having the highest (effective) electron density:

Material	N_e	Absorption edge between 5-20 Å	N_e above abs. edge
B_2O_3	8.7×10^{23}		
Al_2O_3	11.5×10^{23}	7.9 Å (K_{Al})	10.6×10^{23}
Ti_2O_3	12.33×10^{23}		
Cu	22.78×10^{23}	11-13 Å (L)	16.03×10^{23}

Table 1

Using Fresnel's formula for the reflection from an absorbing medium, which was shown to be applicable to x-rays by Nähring⁽⁴⁾ one obtains for the reflectivity as a function of angle:

(4) E. Nähring, Physikal. Zeitschr. 31 - 401 (1930)

$$(Eq. 2) \quad R = \frac{q^2 + \sqrt{(q^2-1)^2 + k^2} - q \sqrt{2(q^2-1)+2} \sqrt{(q^2-1)^2 + k^2}}{q^2 + \sqrt{(q^2-1)^2 + k^2} + q \sqrt{2(q^2-1)+2} \sqrt{(q^2-1)^2 + k^2}}$$

$$q = \frac{29}{\sqrt{28}} \quad k = \frac{\mu \lambda}{4\pi}$$

$\frac{\mu}{\lambda}$ = mass absorption coefficient

Fig. 2 shows the reflectivity of BeO and Cu for various wavelengths as a function of angle.

Choice of Inner Radius.

The choice of the inner radius determines the largest angle of reflection and thereby the shortest wavelength at which the entire telescope is effective. If we have the lower wavelength limit too low we restrict the opening for all wavelengths and if we set it too high we cut off useful information in the shorter wavelength region. The proper choice of the inner radius therefore has to depend on available information about the spectral distribution of the x-rays to be observed. The experimental evidence for the existence of x-rays from extra solar sources by Gursky⁽⁵⁾ et al seems to indicate that x-rays with wavelengths in excess of two angstrom are predominant.

(5) H. Gursky, R. Giacconi, F. R. Paolini and B. Rossi
Phys. Rev. Letters 11, 30 (1963)

A study of the absorption in the interstellar gas by Strom and Strom⁽⁶⁾ shows that for distances of the order of one thousand light years, observation to $\lambda = 20 \text{ \AA}$ might be possible, or for very powerful sources even to $\lambda = 40 \text{ \AA}$. We shall assume from here on that interstellar absorption can be neglected for wavelengths below 20 A.

The spectral distribution of the incoming x-radiation depends strongly on the nature of the source and there seem to be at least two possible types of x-ray sources:

a) Bremsstrahlung radiation from ionized gas clouds with a quantum intensity that is proportional to the wavelength⁽⁷⁾. This type of spectrum makes it desirable to put the short wavelength cutoff as high as possible compatible with interstellar absorption.

b) A much more exciting possibility just recently pointed out by Chiu and Salpeter⁽⁸⁾⁽⁹⁾ is to observe thermal x-rays from neutron stars. Depending on the assumed surface temperature of the neutron stars

(6) S. E. Strom and K. M. Strom

(7) L. Fredrick final report, NASA grant Nsa 480

(8) H. Y. Chiu, Ann. Phys. 26, 364 (1964)

(9) H. Y. Chiu and E. E. Salpeter, Phys. Rev. Letters 12, 413 (1964)

Chiu and Salpeter arrive at spectral distributions peaking between 2.4 and 6.8 Å. Since an x-ray telescope will presumably have a quantum detector it is more appropriate to look at the peak of the quantum emission which lies between 3 and 8.6 Å for the same temperature range.

Since 80% of the quantum emission from a black body is above the wavelength of the peak intensity λ_m and 55 % or 37% above 1.5 or $2\lambda_m$ respectively it is not difficult to design a telescope that performs well for both types of sources.

Design Parameters and Expected Performance for a Proposed Telescope.

To a good approximation the reflecting area of a paraboloidal ring is proportional to $\theta_{\max}^2 \cdot r_2 \cdot \Delta L$, the upper limit on r_2 and ΔL is budgetary and for the sake of argument $r_2 = 125$ cm and $\Delta L = 500$ cm was assumed, this would place the focal plane roughly 60 ft behind the ring*. Taking into account absorption in the mirror material the reflection efficiency was calculated for BeO and Cu mirrors for two different choices of the smaller radius r_1 , corresponding to a 5 cut-off at 5 Å and at 10 Å, assuming a flat spectral distribution.

*The numbers chosen are arbitrary and do not indicate a choice of actual parameters on the part of the NASA.

The results show that a BeO mirror is the best choice at long wavelength and is only insignificantly less effective at short wavelength. It should be easy to manufacture by surface oxidation of an evaporated Be film.

Figure Captions

Fig 1: Paraboloidal mirror.

Fig 2: Reflectivity of Cu and BeO calculated using eq. 2 taking into account the number of effective electrons.

Fig 3: White bars: reflecting area "A" of telescopes with $\Delta L = 500$ cm and $r_2 = 125$ cm for various choices of material and short wavelength cutoff.
Black bars: product of area as defined above and reflectivity.

$$\int_0^A R dA$$

$$y = ar^2$$

$$(r_2 - r_1) = \theta_0 \Delta L$$

$$\theta_0 = \sqrt{2\delta'}$$

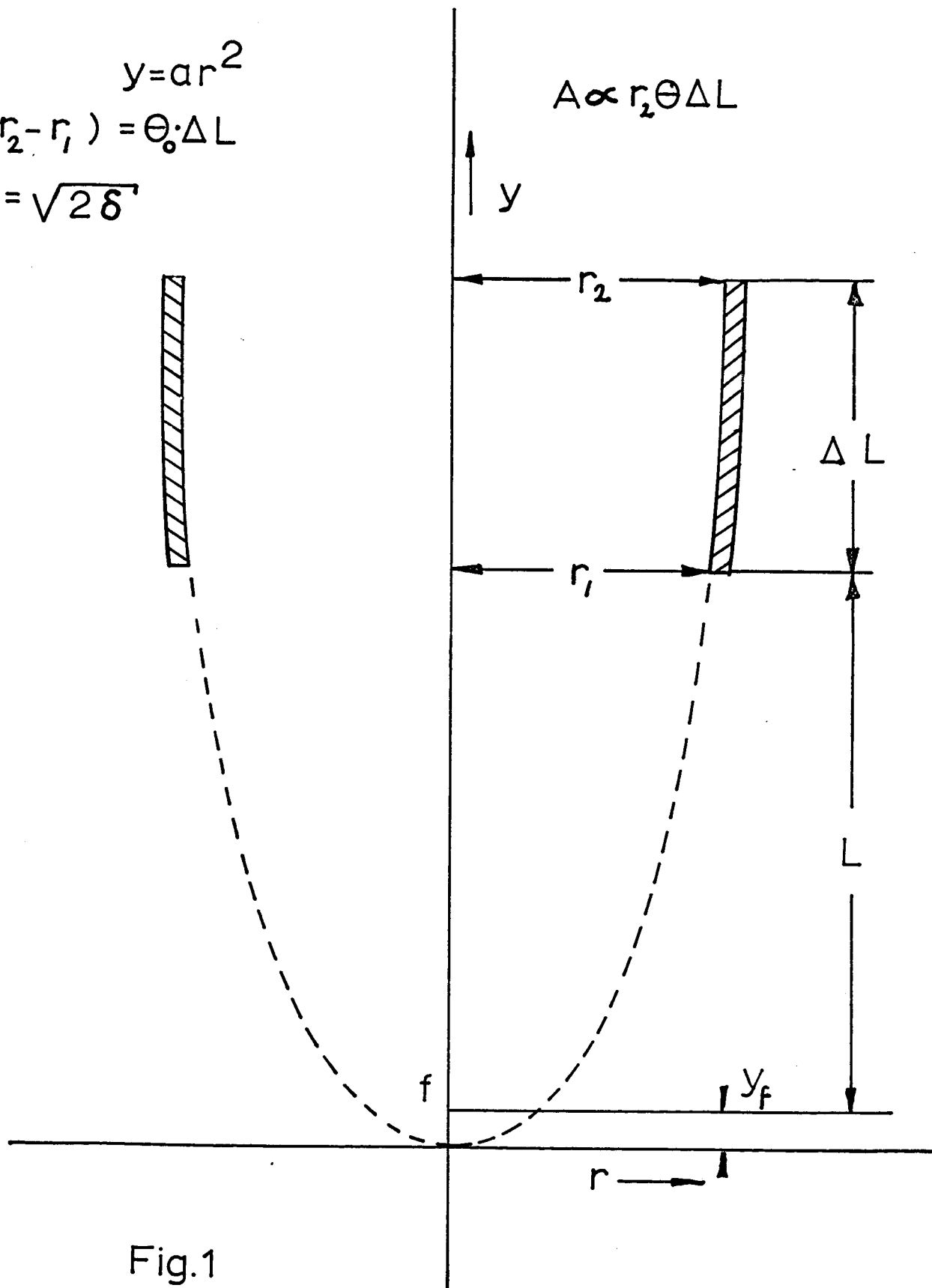
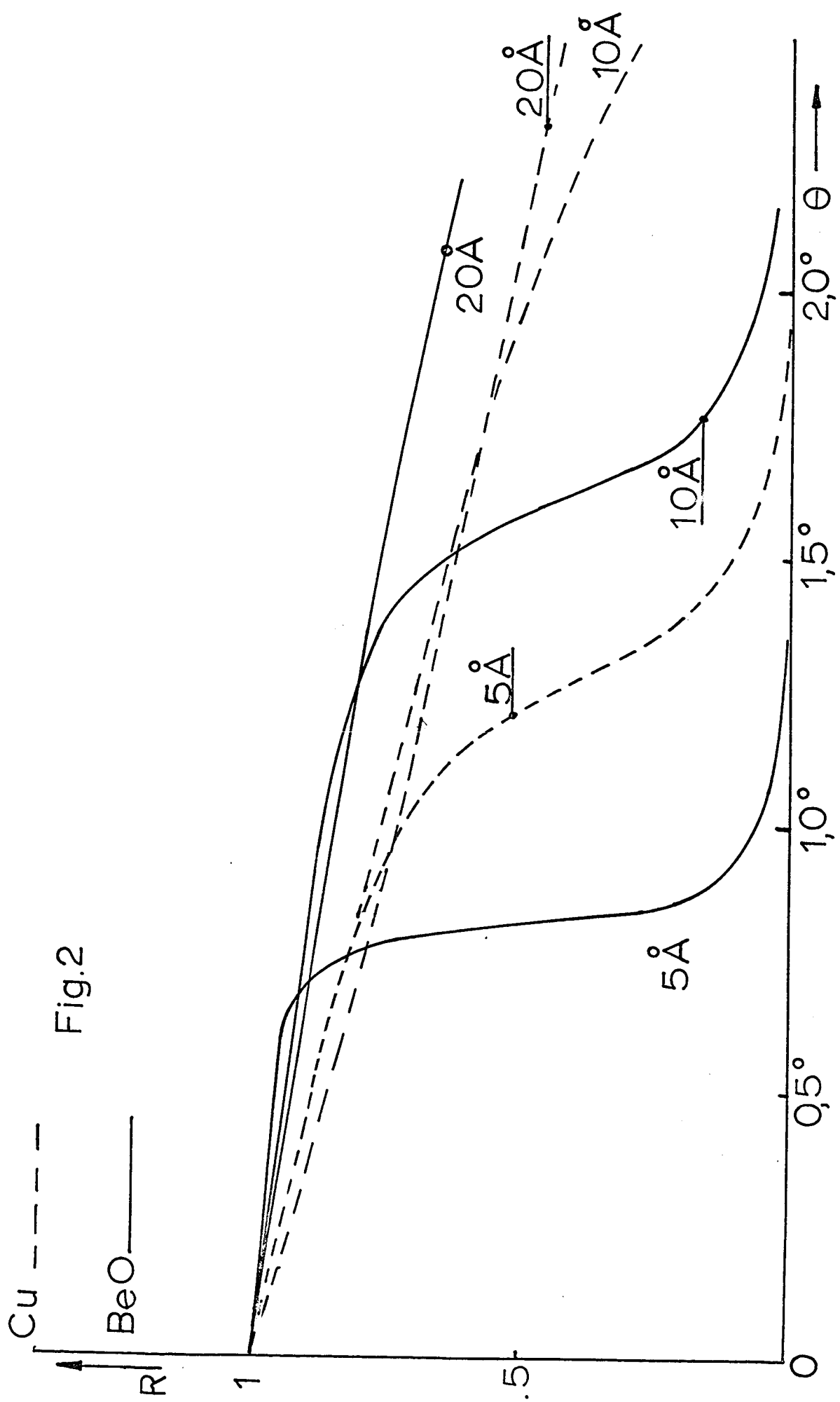


Fig.1



$$\Delta L = 500 \text{ cm}$$

$$r_2 = 125 \text{ cm}$$

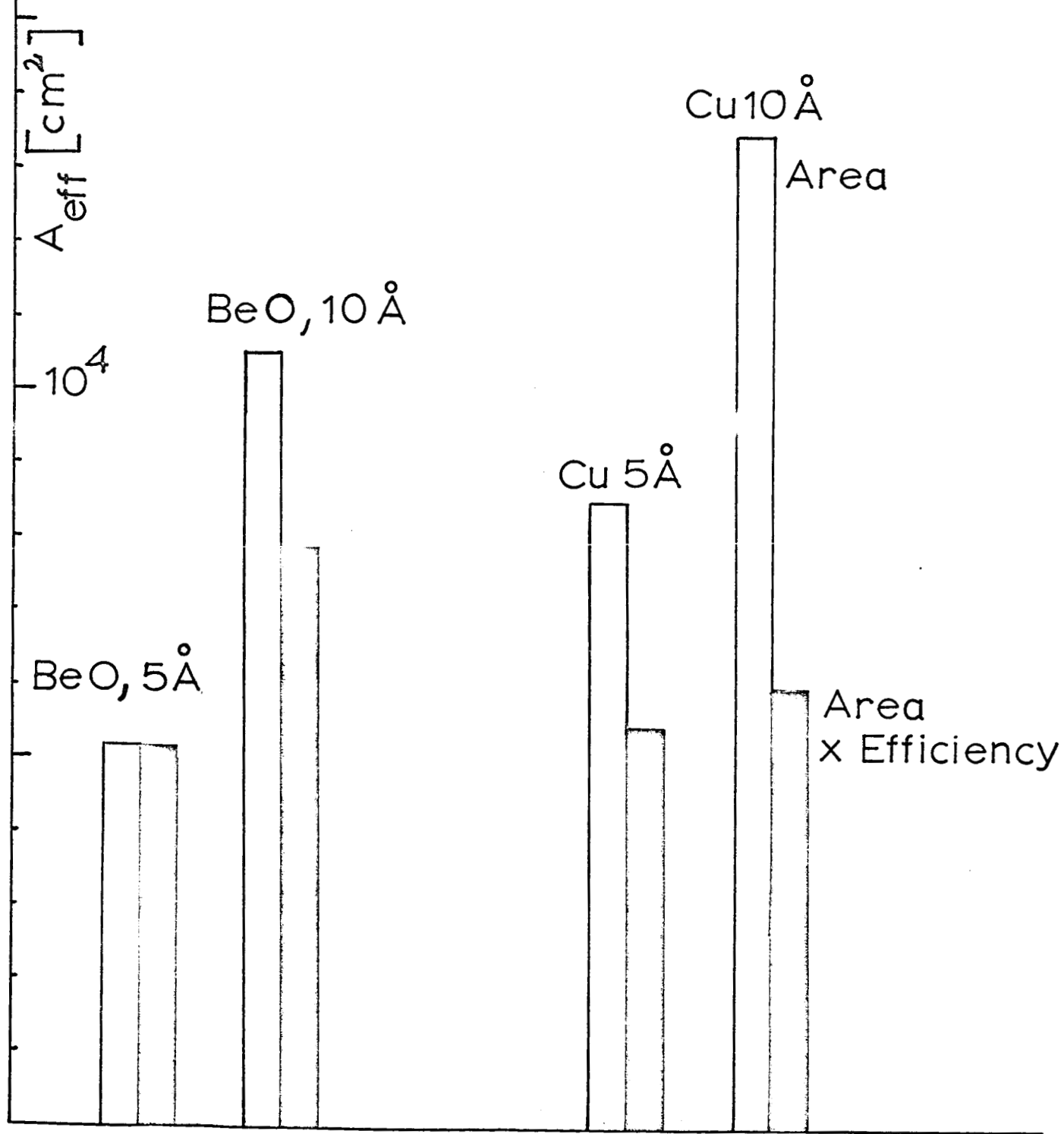


Fig.3